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Patent and Trademark Office
Docket No. 299002052200TRANSMITTAL LETTER TO THE UNITED STATES
DESIGNATED/ELECTED OFFICE (DO/EO/US)
CONCERNING A FILING UNDER 35 U.S.C. § 371

09/786977

U S APPLICATION NO (If known, see 37 C.F.R. § 1.5): To Be Assigned

INTERNATIONAL APPLICATION NO.
PCT/JP99/01952INTERNATIONAL FILING DATE
April 12, 1999PRIORITY DATE CLAIMED
September 11, 1998TITLE OF INVENTION: **METHOD FOR FORMING COMPOUND SEMICONDUCTOR LAYER AND COMPOUND SEMICONDUCTOR APPARATUS**

APPLICANT(S) FOR DO/EO/US: Koji TAKAHASHI and Hidenori KAWANISHI

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. § 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. § 371.
3. ☐ This express request to begin national examination procedures (35 U.S.C. § 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. § 371(b) and PCT Articles 22 and 39(1).
4. ☐ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☒ A copy of the International Application as filed (35 U.S.C. § 371(c)(2))
 - a. ☐ is transmitted herewith (required only if not transmitted by the International Bureau).
 - b. ☒ has been transmitted by the International Bureau.
 - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US)
6. ☒ A translation of the International Application into English (35 U.S.C. § 371(c)(2)) (67 pages).
7. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. § 371(c)(3))
 - a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
 - b. ☒ have been transmitted by the International Bureau.
 - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
 - d. ☐ have not been made and will not be made.
8. ☒ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. § 371(c)(3)) (14 pages).
9. ☒ An unexecuted oath or declaration of the inventors (35 U.S.C. § 371(c)(4)) (2 pages).
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. § 371(c)(5)).

Items 11. to 16. below concern document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 C.F.R. §§ 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 C.F.R. §§ 3.28 and 3.31 is included.
13. ☒ A **FIRST** preliminary amendment (2 pages).
☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
14. ☐ A substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☒ Other items or information: Form PCT/IPEA/401 (10 pages) and Return Receipt Postcard.

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Jennifer Bushard

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| U.S. APPLICATION NO. (If known, see 37 C.F.R. § 1.5) To Be Assigned <div style="font-size: 2em; font-weight: bold; margin-left: 100px;">09/786977</div> | | INTERNATIONAL APPLICATION NO. PCT/JP99/01952 | | DOCKET NUMBER 299002052200 | |
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| 17. <input checked="" type="checkbox"/> The following fees are submitted: BASIC NATIONAL FEE (37 C.F.R. §§ 1.492(a)(1)-(5)): Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO.....\$1000.00 International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO.....\$860.00 International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO.....\$710.00 International preliminary examination fee paid to USPTO (37 CFR 1.482) but all claims did not satisfy provision of PCT Article 33(1)-(4)\$690.00 International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(1)-(4)\$100.00 | | | | CALCULATIONS PTO USE ONLY | |
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| CLAIMS | NUMBER FILED | NUMBER EXTRA | RATE | \$ | |
| Total claims | 31 - 20 = | 11 | x \$18.00 | \$198.00 | |
| Independent claims | 4 - 3 = | 1 | x \$80.00 | \$80.00 | |
| MULTIPLE DEPENDENT CLAIM(S) (if applicable) | | | \$0.00 | \$0 | |
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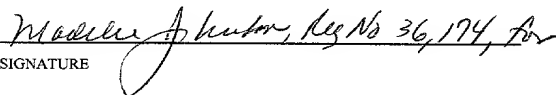
b. ☒ Please charge my **Deposit Account No. 03-1952** referencing docket no. 299002052200 in the amount of \$1,268.00 to cover the above fees. A duplicate copy is being submitted for fee processing.

c. ☒ The Assistant Commissioner is hereby authorized to charge any additional fees that may be required, or credit any overpayment to **Deposit Account No. 03-1952**.

NOTE: Where an appropriate time limit under 37 C.F.R. § 1.494 or 1.495 has not been met, a petition to revive (37 C.F.R. § 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

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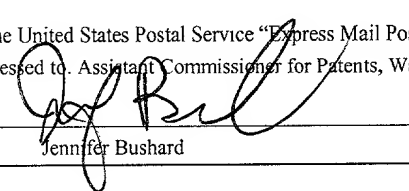
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Jennifer Bushard

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In the application of:

Koji TAKAHASHI and Hidenori
KAWANISHI

International Application No.: PCT/JP99/01952

International Filing Date: April 12, 1999

For: METHOD FOR FORMING
COMPOUND SEMICONDUCTOR
LAYER AND COMPOUND
SEMICONDUCTOR APPARATUS

Examiner: To Be Assigned

Group Art Unit: To Be Assigned

PRELIMINARY AMENDMENT

Box PCT
Commissioner for Patents
Washington, D.C. 20231

Dear Sir:

The above-referenced application is being filed herewith under 35 U.S.C. §371.

Applicants wish to enter the following preliminary amendments to incorporate cross-reference to related applications.

AMENDMENT

In the specification:

At page 1, after the title, please insert the following sentence.

-- This application is a 35 U.S.C. §371 filing of International Patent Application No. PCT/JP99/01952, filed April 12, 1999. This application claims priority benefit of Japanese Patent Application No. 10-259015, filed September 11, 1998. --

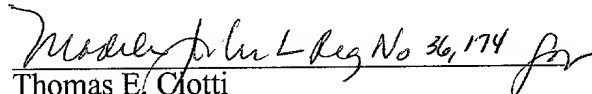
Applicants make this Preliminary Amendment prior to examination and without prejudice or disclaimer of any excluded subject matter, and expressly reserve the right to pursue such subject matter in this application or in one or more continuing applications.

If a telephone call would further prosecution of this case, the Examiner is invited to call the undersigned at (650) 813-5702. In the unlikely event that the transmittal letter is separated from this document and the Patent Office determines that an extension and/or other relief is required, applicant petitions for any required relief including extensions of time and authorizes the Assistant Commissioner to charge the cost of such petitions and/or other fees due in connection with the filing of this document to Deposit Account No. 03-1952 referencing docket no. 299002052200. However, the Assistant Commissioner is not authorized to charge the cost of the issue fee to the Deposit Account.

Respectfully submitted,

Dated: March 12, 2001

By:


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DESCRIPTION

METHOD FOR FORMING COMPOUND SEMICONDUCTOR LAYER AND COMPOUND SEMICONDUCTOR APPARATUS

5

TECHNICAL FIELD

10 The present invention relates to a method for forming a compound semiconductor layer, and more specifically to a method for forming a group III-V compound semiconductor layer containing at least nitrogen and arsenic as a group V element.

BACKGROUND ART

15

20 Recently, as group III-V compound semiconductor materials having a significantly wider field of use as optoelectronics materials, group III-V compound semiconductor materials containing arsenic as a group V element (GaAs, GaInAs, etc.) and nitrogen mix-crystallized therewith have been proposed.

Japanese Laid-Open Publication No. 6-37355
(first conventional example) discloses $Ga_{1-y}In_yN_xAs_{1-x}$

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based compound mix crystal semiconductor materials (z = about 0.04) as new semiconductor materials which are lattice-matched to a GaAs substrate. It is shown that use of such semiconductor materials allows a semiconductor laser for emitting light in a long wavelength band (1.3 to 1.55 μm) to be produced on a low-cost GaAs substrate, which is conventionally impossible.

- 10 PHOTONICS TECHNOLOGY LETTERS, VOL. 10, NO. 4, Apr. 1998, page 487 (second conventional example) discloses producing a semiconductor laser structure on a GaAs substrate. The semiconductor laser structure includes an active layer formed of a quantum well layer which is formed of $\text{Ga}_{0.7}\text{In}_{0.3}\text{N}_{0.01}\text{As}_{0.9}$, and a guide layer, and the active layer is held between upper and lower cladding layers formed of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$. It is reported that such a semiconductor laser realizes continuous oscillation for light having a wavelength of 1.31 μm at room temperature.
- 15 This is the first report that such a continuous oscillation is realized by a semiconductor laser formed of materials lattice-matched to a GaAs substrate.
- 20

For crystal growth of these new semiconductor

materials, a molecular beam epitaxy (MBE) method or an metal organic chemical vapor deposition (MOCVD) method is used. Usable nitrogen source materials include, for example, dimethylhydrazine (DMeHy) and nitrogen gas (N_2)
5 activated by plasma. Crystal growth is conducted by concurrently supplying Ga, In and As source materials and the nitrogen source material(s) described above.

Such group III-V compound crystal semiconductor
10 materials containing a group III-V compound semiconductor having arsenic as a group V element and also containing nitrogen as a group V element mix-crystallized therewith have not been actively studied until recently. The reason is that it is difficult to grow crystals of such
15 semiconductor materials.

For example, GaAsN is considered to be a mix crystal of GaN containing only N as a group V element and GaAs containing only arsenic as a group V element. This
20 mix crystal system have a very large immiscible region (miscibility gap). Therefore, it is difficult even to introduce only several percent of N with GaAs. Thus, it is necessary to carefully select a method and conditions for crystal growth. It is reported that especially

introducing nitrogen with GaAs is significantly influenced by a substrate temperature during crystal growth. As a substrate temperature for such crystal growth, about 500°C is usually selected. The temperature
5 of 500°C is relatively low as a crystal growth temperature of a group III-V compound semiconductor.

Jpn. J. Appl. Phys. Vol. 36, No. 12A, Dec. 1997, page L1572 (third conventional example) shows correlation
10 between the substrate temperature during crystal growth and a nitrogen-mix crystal ratio in the crystal in the case where GaAsN containing monomethylhydrazine (MMeHy) as an N source material is crystal-grown. When the substrate temperature is lower than 500°C, MMeHy is not
15 sufficiently thermally decomposed. Therefore, only a small amount of nitrogen is introduced. By contrast, when the substrate temperature is higher than 500°C, the nitrogen source material is thermally evaporated significantly, such that nitrogen is not introduced into
20 GaAs. It is reported that N can be introduced into the crystal most efficiently at a substrate temperature of about 500°C for these reasons.

In the second conventional example, plasma-

decomposed N_2 is used as a nitrogen source material. In this example also, about 500°C is selected as a crystal growth temperature.

5 Novel compound semiconductor materials
containing nitrogen mix-crystallized with, for example,
GaAs or GaInAs are used for an active layer of a
semiconductor laser. One such example is described above,
in which a GaInNAs layer is used for an active layer of
10 a semiconductor laser. A semiconductor laser using such
a compound semiconductor material does not necessarily
provide superior light emission characteristics over an
equivalent structure using a compound semiconductor
material not containing nitrogen. For example, in the
15 publication showing the above-described second
conventional example, semiconductor lasers having
structures similar to one another are produced. One of
these semiconductor lasers uses GaInAs not containing
nitrogen for an active layer (quantum well), and the other
20 semiconductor laser uses GaInNAs containing nitrogen.
It is reported that when 1% of nitrogen is contained, the
oscillation threshold current becomes four times larger
and the light emission efficiency is reduced to about $2/3$.
It is also reported that when a small amount of nitrogen

is contained, the light emission efficiency is drastically reduced.

As one cause of reduction in the light emission efficiency, it can be pointed out that the crystal growth temperature is too low according to the conventional crystal growth method and therefore crystals having sufficient crystallinity are not obtained.

For example, in the case of GaAsN, a crystal is produced by introducing N into GaAs by causing crystal growth to proceed in a state of non-equilibrium at a low growth temperature (about 500°C). Such a crystal cannot be produced in a state of thermal equilibrium. GaAsN can be considered to be a mix crystal of GaAs and GaN. The optimum growth temperature of GaAs is 600°C to 750°C, and the optimum growth temperature of GaN is 900 to 1000°C. As compared to these temperatures, about 500°C cannot be considered to be the optimum growth temperature for GaAsN-based compound mix crystal semiconductor materials.

It is assumed, for example, that in a semiconductor laser including an active layer and upper

and lower cladding layers sandwiching the active layer, the active layer is formed of GaInNAs and the upper and lower cladding layers are formed of, for example, AlGaAs, GaInP, InGaAsP or AlGaInP. For producing such a semiconductor laser, the crystal growth temperature for the upper and lower cladding layers formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0, i > 0, j \geq 0$) is usually set to be a low substrate temperature (about 500°C) in conformity with the crystal growth temperature for the GaInNAs active layer. As described above, the cladding layers crystal-grown at such a low substrate temperature do not have sufficient crystallinity. Unless the lower cladding layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0, i > 0, j \geq 0$) which acts as an underlying layer of the GaInNAs active layer has sufficient crystallinity, the crystal defect of the lower cladding layer is transferred to the GaInNAs active layer which is crystal-grown on the lower cladding layer. Accordingly, when a laser structure is produced at such a low temperature, satisfactory light emission characteristics cannot be provided, and the laser device deteriorates quickly. Such a conventional low temperature crystal growth method is considered to be performed in order to meet a requirement for provision of a novel material by introducing nitrogen rather than

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a requirement for improvement in the light emission characteristics by growth of GaAsN or GaInNAs at a high temperature.

5 As an attempt to improve light emission characteristics, there is a report on the effect of heat treatment performed after the crystal growth. The abstract of Jpn. J. Appl. Phys. Spring 1998, 28p-ZM-12 reports that the light emission intensity becomes 25 times
10 higher by heating GaAsN (nitrogen composition ratio: 0.79%) at 700°C for 10 minutes in a hydrogen atmosphere. However, the studies of the present inventors found that the laser characteristics of a semiconductor laser using GaInNAs for an active layer
15 cannot be improved to a practically usable level by merely performing heat treatment after the crystal growth. The studies of the present inventors also found that means for providing a satisfactory crystal structure during crystal growth is necessary instead of such a treatment
20 performed after the crystal growth.

DISCLOSURE OF THE INVENTION

The present invention has an objective of solving

the above-described problems. Namely, it is an objective of the present invention to provide a method for forming a group III-V compound semiconductor layer containing a group III-V compound semiconductor having arsenic as a group V element and also containing nitrogen mix-crystallized therewith, the group III-V compound semiconductor layer having satisfactory light emission characteristics.

10 A method for forming a compound semiconductor layer according to the present invention includes the step of crystal-growing a group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements on a single crystal substrate. The step of
15 crystal-growing the compound semiconductor layer includes the step of supplying a nitrogen source material to the single crystal substrate so that the nitrogen source material interacts with aluminum at least on a crystal growth surface of the compound semiconductor
20 layer.

In another aspect of the invention, a method for forming a compound semiconductor layer according to the present invention includes the step of crystal-growing

a group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements on a single crystal substrate. The step of crystal-growing the compound semiconductor layer includes the step of
5 supplying an aluminum source material to the single crystal substrate concurrently with a nitrogen source material.

In still another aspect of the invention, a method
10 for forming a compound semiconductor layer according to the present invention includes the step of crystal-growing a group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements on a single crystal substrate. The step of
15 crystal-growing the compound semiconductor layer includes the step of supplying a nitrogen source material to a crystal surface of the compound semiconductor layer in a state where the group III atoms containing aluminum are exposed to the crystal surface.

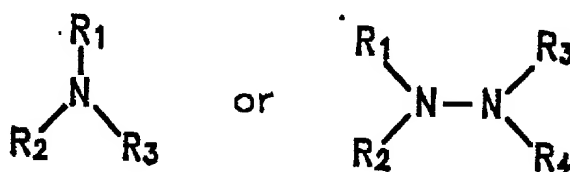
20

In one preferable embodiment, an aluminum-mix crystal ratio in a group III element in the compound semiconductor layer is 0.02 or higher.

In one preferable embodiment, the step of crystal-growing the compound semiconductor layer is performed at a temperature of the single crystal substrate in the range of 500°C or higher and 750°C or lower, and
5 more preferably in the range of 600°C or higher and 750°C or lower.

In one preferable embodiment, the nitrogen source material contains

10



15

where R₁, R₂, R₃ and R₄ are hydrogen or a lower alkyl group.

In one preferable embodiment, more than 0% and less than 50% of the crystal growth surface of the compound
20 semiconductor layer is covered with group V atoms.

In one preferable embodiment, the step of crystal-growing the compound semiconductor layer further includes the step of supplying a group III source material

containing aluminum and the step of supplying an arsenic source material, wherein a process sequentially including the step of supplying the group III source material, the step of supplying the nitrogen source material, and the
5 step of supplying the arsenic source material is performed at least once.

In one preferable embodiment, the single crystal substrate has a {100} plane as a principal plane.

10

In one preferable embodiment, the step of crystal-growing a layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0, i > 0, j \geq 0$) on the single crystal substrate is further included. The step of crystal-growing the compound
15 semiconductor layer and the step of growing the crystal formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ are performed at the same temperature.

In one preferable embodiment, the step of
20 crystal-growing the compound semiconductor layer is performed after the step of crystal-growing the layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$.

In one preferable embodiment, the step of

crystal-growing the compound semiconductor layer is performed before the step of crystal-growing the layer formed of $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{As}_z\text{P}_{1-z}$.

5 In one preferable embodiment, the compound semiconductor layer further contains indium.

10 A compound semiconductor apparatus according to the present invention includes at least one group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements. The compound semiconductor layer is formed in accordance with any one of the methods for forming a compound semiconductor layer described above.

15 In one preferable embodiment, the compound semiconductor apparatus is a light emitting device including at least a light emitting layer, and the light emitting layer includes the compound semiconductor layer.

20 In one preferable embodiment, the light emitting layer is formed of $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{N}_z\text{As}_{1-z}$ ($0 < x, y, z < 1$), and an Al-mix crystal ratio x in the light emitting layer is 0.02 or higher and 0.20 or lower, and more preferably 0.02

or higher and 0.10 or lower.

In one preferable embodiment, the light emitting device further includes a cladding layer, a guide layer
5 and/or a barrier layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0$, $i > 0$, $j \geq 0$).

Hereinafter, the function of the present invention will be described.

10

According to the present invention, a nitrogen source material is supplied to a single crystal substrate so that the nitrogen source material interacts with aluminum at least on a crystal growth surface of a compound
15 semiconductor layer. Therefore, a decomposition reaction of the nitrogen source material on the surface of the substrate is promoted, and thus thermal evaporation of nitrogen is suppressed. Consequently, even when the crystal growth temperature is raised to be relatively high
20 (600°C or higher and 750°C or lower), a sufficient amount of nitrogen is introduced. As a result, a crystal having satisfactory crystallinity and especially satisfactory light emission characteristics can be provided. A crystal formed of AlGaAs , GaInP , InGaAsP or AlGaInP has

5 satisfactory crystallinity as a result of being
crystal-grown at a relatively high temperature which is
equal to the above crystal growth temperature.
Accordingly, for producing a multi-layer film containing
10 such a crystal layer on at least one surface of a group
III-V compound semiconductor crystal layer, the growth
temperature of the group III-V compound semiconductor
crystal can be adjusted to be in a temperature range which
is optimum for the above-described materials. Thus, the
10 growth temperature of the multi-layer film can be
maintained so as to be high. Therefore, a hetero junction
of high quality crystals can be formed.

BRIEF DESCRIPTION OF THE DRAWINGS

15

Figure 1 is a schematic cross-sectional view
illustrating a single quantum well structure produced in
Examples 1 through 15 and 17 through 19, and Comparative
examples 1 through 14.

20

Figure 2 is a graph illustrating the dependency
of the nitrogen-mix crystal ratio of a well layer on the
Al-mix crystal ratio, the well layer being crystal-grown
in Examples 1 through 5 and Comparative example 1 at a

constant growth temperature under constant source supply conditions.

Figure 3 is a graph illustrating the dependency
5 of the nitrogen-mix crystal ratio of a well layer on the
growth temperature, the well layer being crystal-grown
under constant source supply conditions. Line (a) is a
plot of the results of Examples 1, 6 through 9 and
Comparative examples 2 and 3 in which an Al source material
10 is contained, and line (b) is a plot of the results of
Comparative examples 4 through 7 in which no Al source
material is contained.

Figure 4 is a graph illustrating the dependency
15 of photoluminescence light emission intensity of a
crystal containing 1% of nitrogen mix-crystallized ($z = 0.01$) on the growth temperature. Line (a) is a plot of
the results of Examples 10 through 14 and Comparative
examples 8 and 9 in which an Al source material is contained,
20 and line (b) is a plot of the results of Comparative
examples 10 and 11 in which no Al source material is
contained.

Figure 5 is a graph illustrating a change in the

concentration of nitrogen which is introduced in a film when the supply amount of As changes while the growth temperature and supply amounts of source materials other than As are maintained in Example 1 and Comparative
5 examples 12 through 14.

Figure 6 is a diagram illustrating a source material supply sequence for growing a well layer in Example 15.

10

Figure 7 is a schematic cross-sectional view of a semiconductor laser produced in Example 16 seen from a light emission surface of the laser.

15

Figure 8 is a graph illustrating the relationship between the Al, N and In-mix crystal ratios in an AlGaInNAs well layer in a semiconductor laser for emitting light having a wavelength of 1.3 μm .

20

Figure 9 is a graph illustrating the dependency of oscillation threshold current of a semiconductor laser produced in Example 16 on the Al-mix crystal ratio in a well layer of the semiconductor laser.

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BEST MODE FOR CARRYING OUT THE INVENTION

Examples of the present invention will be described in detail together with Comparative examples.

5 (Example 1)

In this example, as shown in Figure 1, a multi-layer film 10 having a single quantum well structure is crystal-grown on a GaAs substrate 1 using an MBE (molecular beam epitaxy) method. The multi-layer film 10 includes an $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ lower barrier layer 2 having a thickness of about 0.5 μm , an $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}_{0.015}\text{As}_{0.005}$ well layer (light emission layer) 3 having a thickness of about 6 nm, and an $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ upper barrier layer 4 having a thickness of about 0.1 μm , which are laminated.

15

Hereinafter, a method for forming a compound semiconductor layer in this example will be described. The method is different from the conventional methods in that an appropriate amount of Al source material is added during the crystal growth of the light emission layer in this example.

An MBE apparatus containing metal Ga, metal Al and As, as solid sources, and DMeHy (dimethylhydrazine) as a

gas source was used to supply these materials to a chamber. The substrate 1 was irradiated with a molecular beam of each source material while maintaining the temperature of the GaAs substrate 1 having a {100} plane as a principal plane at 650°C, thereby performing crystal growth. Thus, the single quantum well structure shown in Figure 1 was produced. The strength of each molecular beam for crystal growth by the MBE method was as follows: Ga: about 3.6×10^{-7} torr; Al: about 1.9×10^{-8} torr for growing the well layer 3 and about 3.3×10^{-7} torr for growing the barrier layers 2 and 4; As₄: about 4.7×10^{-6} torr; and DMeHy: about 3.6×10^{-6} torr. Throughout the crystal growth process, all the necessary source materials were concurrently supplied. Especially for producing the AlGaAs well layer 3, it was important to concurrently supply Al and DMeHy as described below with reference to Figures 2 through 4.

In this manner, the Al_{0.3}Ga_{0.7}As lower barrier layer 2, the Al_{0.05}Ga_{0.95}N_{0.015}As_{0.035} well layer (light emission layer) 3, and the Al_{0.3}Ga_{0.7}As upper barrier layer 4 were sequentially crystal-grown on the GaAs substrate 1. In the light emission layer 3 of the multi-layer film 10, the aluminum-mix crystal ratio was 0.05, and the

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Figure 1. The effect of the number of iterations (n) on the accuracy of the proposed algorithm. The error rate decreases as the number of iterations increases. The error rate stabilizes at approximately 0.01 after 100 iterations.

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so as to provide Al-mix crystal ratios of 0.02, 0.1, 0.15 and 0.2, respectively. The measurement results of the nitrogen-mix crystal ratios in the well layer of these multi-layer films are shown in Figure 2.

5

(Comparative example 1)

A multi-layer film was produced in a similar manner to that of Example 1 except that the Al-mix crystal ratio was zero by not supplying Al source material during
10 the crystal growth process. The nitrogen-mix crystal ratio in the well layer of the multi-layer film is shown in Figure 2.

Hereinafter, Examples 1 through 5 and Comparative
15 example 1 will be discussed with reference to Figure 2. Figure 2 is a graph illustrating the dependency of the nitrogen-mix crystal ratio in the well layer on the supply amount of Al when crystal growth was performed under constant source supply conditions. When the Al source
20 material was added in such an amount that the Al-mix crystal ratio in solid phase substantially exceeded 2% (Al-mix crystal ratio $x = 0.02$), the introduction amount of nitrogen increased and thus the effect of adding the Al source material was exhibited.

(Examples 6 through 9)

Multi-layer films were produced in a similar manner to that of Example 1 except that the substrate temperature during the crystal growth process was set to be 500°C, 550°C, 600°C and 750°C, respectively. The measurement results of the nitrogen-mix crystal ratio in the well layer of these multi-layer films are shown in Figure 3.

10

(Comparative examples 2 and 3)

Multi-layer films were produced in a similar manner to that of Example 1 except that the substrate temperature during the crystal growth process was set to be 400°C and 450°C, respectively. The measurement results of the nitrogen-mix crystal ratios in the well layer of these multi-layer films are shown in Figure 3.

15

(Comparative examples 4 through 7)

Multi-layer films were produced in a similar manner to that of Example 1 except that no Al source material was supplied and that the substrate temperature during the crystal growth process was set to be 450°C, 500°C, 550°C and 600°C, respectively. The measurement

20

results of the nitrogen-mix crystal ratios in the well layer of these multi-layer films are shown in Figure 3.

Hereinafter, Examples 1, 6 through 9 and Comparative examples 2 through 7 will be discussed with reference to Figure 3.

Figure 3 is a graph illustrating the dependency of the nitrogen-mix crystal ratio in the well layer on the growth temperature. In the figure, line (a) is a plot of the results of Examples 1, 6 through 9 and Comparative examples 2 through 3 in which Al was contained; and line (b) is a plot of the results of Comparative examples 4 through 7 in which Al was not contained.

15

When Al was not contained, the nitrogen-mix crystal ratio was maximum at the substrate temperature of about 500°C, and the nitrogen-mix crystal ratio was lower when the substrate temperature was either higher or lower than this. In samples obtained by performing crystal growth at 450°C and 600°C, the nitrogen-mix crystal ratio was not detected in an amount which can be detectable as a part of the composition. The reason is that when the substrate temperature is too low, the source

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In the case where Al was contained, the introduction amount of nitrogen was maximum at the substrate temperature of 500°C as in the case where no Al was contained. However, even when the substrate temperature was higher than this, the introduction amount of nitrogen was not significantly reduced. It was found from Figure 3 that when Al was contained, the introduction amount of nitrogen was improved in the range of the substrate temperature of 450°C through 750°C, as compared to the case where no Al was contained. It was also found that the substrate temperature can be raised to the vicinity of 600 to 750°C, which is the optimum growth temperature range for AlGaAs, InGaP, InGaAsP, AlGaInP and the like. The nitrogen-mix crystal ratio was high even at a substrate temperature of lower than 500°C (for example, 450°C) when Al was contained, unlike when Al was not

contained, for the following reason. Since the Al source material, which has a high reactivity, was supplied concurrently with the nitrogen source material, decomposition of the source materials on the surface of the substrate was promoted. The nitrogen-mix crystal ratio was increased when the substrate temperature was higher than 500°C and also was unlikely to be reduced in accordance with a rise in the substrate temperature, unlike when Al was not contained, for the following reason.

10 Since Al is not substantially thermally evaporated, a crystal containing Al itself is unlikely to be thermally etched. Specifically, generation of Al-N bonds having a strong bonding force during the crystal growth suppresses thermal leaving of nitrogen. When the

15 substrate temperature was higher than 750°C, thermal evaporation of Ga was excessive, and thus it was difficult to produce a crystal having a flat surface.

(Example 10)

20 A multi-layer film was produced in a similar manner to that of Example 1 except that the strength of the molecular beam of the N source material (DMeHy) during the crystal growth was adjusted to be about 2.4×10^{-6} torr so as to provide a nitrogen-mix crystal ratio of 0.01.

The measurement result of photoluminescence light emission intensity of this multi-layer film is shown in Figure 4 as value "1".

5 (Examples 11 through 14)

Multi-layer films were produced in a similar manner to that of Example 10 except that the substrate temperature during the crystal growth was set to be 500°C, 550°C, 600°C and 750°C respectively and that the strength
10 of the molecular beam of the nitrogen source material (DMeHy) was appropriately changed in order to provide a nitrogen-mix crystal ratio of 0.01 as in Example 10. The measurement results of photoluminescence light emission
15 4, with the results of Example 10 used as a reference.

(Comparative examples 8 and 9)

Multi-layer films were produced in a similar manner to that of Example 10 except that the substrate
20 temperature during the crystal growth was set to be 400°C and 450°C respectively and that the strength of the molecular beam of the nitrogen source material (DMeHy) was appropriately changed in order to provide a nitrogen-mix crystal ratio of 0.01 as in Example 10. The

measurement results of photoluminescence light emission intensity of these multi-layer films are shown in Figure 4, with the results of Example 10 used as a reference.

5 (Comparative examples 10 and 11)

Multi-layer films were produced in a similar manner to that of Example 10 except that no Al source material was supplied, that the substrate temperature during the crystal growth was set to be 500°C and 550°C
10 respectively, and that the strength of the molecular beam of the nitrogen source material (DMeHy) was appropriately changed in order to provide a nitrogen-mix crystal ratio of 0.01 as in Example 10. The measurement results of photoluminescence light emission intensity of these
15 multi-layer films are shown in Figure 4, with the results of Example 10 used as a reference.

Hereinafter, Examples 10 through 14 and Comparative examples 8 through 11 will be discussed with
20 reference to Figure 4.

Figure 4 is a graph illustrating the dependency of the photoluminescence light emission intensity of a crystal containing 1% of nitrogen (z: 0.01) on the growth

temperature. In the figure, line (a) is a plot of the results of Examples 10 through 14 and Comparative examples 8 and 9 in which Al was contained; and line (b) is a plot of the results of Comparative examples 10 and 11 in which
5 Al was not contained.

When Al was not contained, as can be appreciated from Figure 3, at a substrate temperature of higher than 550°C, it was difficult to introduce nitrogen and
10 therefore it was difficult to produce a crystal itself. As can be appreciated from Figure 4, at a substrate temperature of higher than 550°C, it was difficult to grow a crystal and therefore the light emission intensity was reduced. When Al was contained, as can be appreciated
15 from Figure 3, crystal growth is possible at a substrate temperature of up to 750°C. Thus, a sufficient amount of nitrogen can be introduced even at a high substrate temperature. From Figure 4, it was found that the light emission intensity is improved than when Al was not
20 contained in the range of the substrate temperature of 500°C to 750°C. It was found that the light emission intensity is high especially at a substrate temperature of 600°C or higher. In the conventional methods, priority was put on increasing the introduction amount of nitrogen,

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and for this purpose, crystal growth was intentionally performed at a low substrate temperature (500°C) so as to cause the crystal growth to proceed in a more non-equilibrium state. According to the present invention, unlike the conventional methods, nitrogen can be introduced at a higher temperature. Therefore, crystal growth can be performed in a temperature range which is close to an optimum growth temperature for GaAsN-based mix crystal materials.

10

As described above, as can be appreciated from Examples 1, 6 through 9, Comparative examples 2 through 7, Examples 10 through 14, and Comparative examples 8 through 11 with reference to Figures 3 and 4, the substrate temperature at which a sufficient amount of nitrogen can be introduced and satisfactory light emission characteristics are obtained is 500°C or higher and 750°C or lower, and more preferably 600°C or higher and 750°C or lower.

20

(Comparative examples 12 through 14)

Multi-layer films were produced in a similar manner to that of Example 1 except that the strength of the molecular beam of As, during the crystal growth process

was set to be about 8.0×10^{-6} torr, about 2.0×10^{-5} torr, and 3.0×10^{-5} torr, respectively. The measurement results of the nitrogen-mix crystal ratios in the well layer of these multi-layer films are shown in Figure 5.

5 From the results of a RHEED observation, the surface reconstruction was (2×4) (about 75% of the crystal growth surface was covered with arsenic and nitrogen as group V elements).

10 Hereinafter, Example 1 and Comparative examples 12 through 14 will be discussed with reference to Figure 5. Figure 5 is a graph illustrating the nitrogen-mix crystal ratio in a well layer when the supply amount of As_4 was changed while maintaining the supply amount of the
15 source materials other than As_4 and the growth temperature. It was found from Figure 5 that the conditions of supplying As_4 influences the crystal growth in addition to the supply amount of Al and the growth temperature. Figure 5 also shows the pattern of surface reconstruction obtained from
20 the results of a RHEED observation during the growth. Under the growth conditions of supplying an excessive amount of As_4 which results in a surface reconstruction of (2×4) (about 75% of the crystal growth surface was covered with arsenic and nitrogen as group V elements),

the nitrogen-mix crystal ratio was small. By contrast, under the growth conditions which result in a surface reconstruction of (3×1) (about 40% of the crystal growth surface was covered with arsenic and nitrogen), the nitrogen-mix crystal ratio increased by an amount equal to or more than the amount of an increase caused by the N/As ratio when the source materials were supplied. Under the conditions containing a small amount of As which results in a surface reconstruction of (4×2) (0% of the crystal growth surface was covered with arsenic and nitrogen), the surface of the resultant film was very rough due to generation of Ga droplets.

It is appreciated from the above that decomposition of DMeHy at the surface of the crystal as a nitrogen source material and adsorption of the nitrogen atoms obtained by decomposition vary in accordance with the degree of exposure of the group III atoms to the surface during the growth. In the optimum growth conditions, the group III atoms are exposed on at least a half of the surface (60% in Example 1) and the group III atoms do not generate an excessive amount of droplets. In the case of AlGaAsN in Example 1, a surface reconstruction of (3×1) was obtained in the optimum growth conditions. This

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methods. Even when the crystal growth temperature is as high as described above, it is possible to introduce a sufficient amount of nitrogen or indium so as to grow a crystal having satisfactory crystallinity and especially

5 satisfactory light emission characteristics. Especially even at a temperature as high as the temperature range suitable for growing AlGaAs, GaInP, InGaAsP and AlGaInP having satisfactory crystallinity, the introduction amount of nitrogen (nitrogen-mix crystal

10 ratio) is not reduced. Therefore, the present invention is suitable for producing a multi-layer film structure including AlGaAs as a layer on at least one surface of a group III-V semiconductor material layer which both contains nitrogen and arsenic as group V elements.

15 Additionally, when nitrogen is introduced utilizing a decomposition reaction of a nitrogen compound source material on the substrate surface, decomposition efficiency and the introduction efficiency of the nitrogen source material are significantly improved owing

20 to the presence Al, which has a high reactivity, on the surface of the substrate.

The above-described functions and effects were provided only when a small amount of Al was added to the

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GaAsN layer to be produced. Such special functions and effects obtained by the addition of Al were not provided when indium (In) as a group III element, or phosphorus (P) or antimony (Sb) as a group V element was added. The concurrent addition of Al and In provides another effect of suppressing thermal evaporation of In, which has a high pressure when vaporized and thus is easily evaporated. This is convenient for precisely controlling an In composition in mixed-crystal materials containing In.

10

(Example 15)

In this example, as in Example 1, a multi-layer film 10 having a single quantum well structure is crystal-grown on a GaAs substrate 1 using a CBE (chemical beam epitaxy) method. The multi-layer film 10 includes an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ lower barrier layer 2 having a thickness of about $0.5\ \mu\text{m}$, an $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}_{0.05}\text{As}_{0.95}$ well layer (light emission layer) 3 having a thickness of about $7\ \text{nm}$, and an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ upper barrier layer 4 having a thickness of about $0.1\ \mu\text{m}$, which are laminated.

Hereinafter, a method for forming a compound semiconductor layer in this example will be described. The method is different from the conventional methods in

that in this example, one process cycle, including the step of supplying a group III source material containing an appropriate amount of Al source material, the step of supplying a nitrogen source material to a surface of the group III source material, and the step of supplying an arsenic source material is repeated a plurality of times to perform crystal growth.

A CBE apparatus containing TMGa (trimethyl gallium), AsH₃ (arsine), NH₃ (ammonia) and TMAI (trimethyl aluminum) was used to supply these source materials to a chamber. A crystal was grown on the substrate 1 while maintaining the temperature of the GaAs substrate 1 having a {100} plane as a principal plane at 600°C. Thus, the above-described single quantum well structure was produced. The strength of each molecular beam for crystal growth by the CBE method was as follows: TMGa: about 3.5×10^{-7} torr; TMAI: about 1.5×10^{-7} torr for growing the barrier layers 2 and 4 and about 1.8×10^{-8} torr for growing the well layer 3; AsH₃: about 8.0×10^{-6} torr; and HN₃: about 1.0×10^{-5} torr.

Throughout the crystal growth process, all the necessary source materials were concurrently supplied for

10

Figure 6 including parts (a) through (d) is a timing diagram for supplying source material gases. After the lower barrier layer 2 was grown by concurrently supplying all the source materials, alternate supply of the source materials was begun. First, in step A, TMGa and TMAI were supplied for 2 seconds, thereby forming an end surface of the group III source material. Next, in step B, NH_3 was supplied for 3 seconds, thereby performing partial nitriding. Then, in step C, AsH_3 was supplied for 2 seconds, thereby forming one molecular layer of AlGaAsN . By repeating the process cycle including steps A through C an appropriate number of times, the AlGaAsN layer (well layer) 3 having a prescribed thickness was obtained. Thereafter, all the source materials were concurrently

supplied, thereby growing the upper barrier layer 4.

In this manner, the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ lower barrier layer 2, the $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}_{0.05}\text{As}_{0.95}$ well layer (light emission layer) 3, and the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ upper barrier layer 4 were sequentially crystal-grown on the GaAs substrate 1. In the light emission layer 3 of the multi-layer film 10, the aluminum-mix crystal ratio was 0.05 and the nitrogen-mix crystal ratio was 0.05. The composition of $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}_{0.05}\text{As}_{0.95}$ forming the well layer 3 has a -1% of tensile strain with respect to the GaAs substrate.

As a result of measuring photoluminescence light emission intensity of samples produced in this manner at room temperature, it was confirmed that an AlGaAs/AlGaAs quantum well having satisfactory light emission characteristics was produced. An AlGaAs/GaNAs/AlGaAs quantum well was produced by supplying a nitrogen source material by a similar method to that of this example so as to mix-crystal nitrogen in a similar amount to that of this example, but without adding Al as in the conventional methods. The introduction amount of nitrogen was lower than that of this example by one order of magnitude. The multi-layer

film produced in this example showed no non-uniformity in the light emission wavelength or light emission intensity, and exhibited a high light emission intensity and a very smooth morphology of the surface of the crystal.

5

In this example, the group III source material, the nitrogen source material, and the arsenic source material were independently and sequentially supplied unlike in Examples 1 through 14 in which all the source materials were concurrently supplied. The growth method in this example positively utilizes that when NH_3 as a nitrogen source material is supplied while the group III element containing Al is on the top surface of the substrate, the thermal decomposition of NH_3 is promoted. By this method, the introduction efficiency of nitrogen is especially improved. The special improvement in introduction efficiency of nitrogen will be described in more detail with reference to Figure 6.

20

First in step A of Figure 6, the substrate is exposed to TMGa and TMAI capable of supplying Ga and Al, the total thickness of Ga and Al being equal to or less than the thickness of one atomic layer. The group III atom may be supplied in an any amount as long as a thickness

thereof is equal to less than the thickness of one atomic layer. In the case where an organic metal compound such as, for example, TMGa or TMAI is used as a group III source material, an atomic layer epitaxy mode may be used, by
5 which the growth stops automatically when the group III element is grown to the thickness of one atomic layer. Next, in step B, NH_3 is supplied. The supply time is controlled so that nitrogen is introduced in such an amount to provide a nitrogen-mix crystal ratio in solid
10 phase of 5% (nitrogen-mix crystal ratio $z = 0.05$). By supplying NH_3 in the state where the group III atoms containing active Al are exposed to the surface of the substrate, the adsorption/decomposition of NH_3 is promoted by a reaction at the surface. If AsH_3 is supplied
15 concurrently with NH_3 , the surface of the substrate is quickly covered with As atoms, which have a lower decomposition temperature and thus are more easily adsorbed than NH_3 . As a result, the probability of the decomposition reaction of NH_3 at the surface is reduced.
20 In step C, AsH_3 is independently supplied, thereby terminating the group III atoms, having no nitrogen on the substrate surface adsorbed thereto, with arsenic. AsH_3 is supplied in step C in an amount corresponding to 0.95 of an atomic layer. As is adsorbed only to the group

III atoms which have not been bonded with nitrogen atoms on the surface of the substrate, and the other extra portion of As leaves without being adsorbed since no group III atoms are available to react. The nitrogen atoms already chemically adsorbed in step B have very large Ga-N and Al-N bonding energies. Therefore, these nitrogen atoms are not substituted with the As atoms supplied after the nitrogen atoms. Each time the process including steps A through C is performed once, an AlGaAsN layer having a thickness of one molecular layer or less is formed. For growing a thick layer, this process is repeated a plurality of times.

While a compound containing arsenic and nitrogen as group V elements (for example, GaAsN) is crystal-grown, the compound is easily phase-separated into an arsenic compound (GaAs) and a nitrogen compound (GaN). Therefore, it is difficult to grow a crystal containing arsenic and nitrogen uniformly mixed together. By supplying an arsenic source material and a nitrogen source material with a time delay therebetween as in this example, neither interference nor competition between the arsenic atoms and the adsorption site of the nitrogen atoms occurs. As a result, a crystal containing arsenic and nitrogen

randomly mixed is formed. In other words, by supplying only a nitrogen source material to a surface at which active group III atoms, generated by adding an aluminum source material, are exposed, the decomposition
5 efficiency and the introduction efficiency of the nitrogen source material are significantly improved without causing competition between the adsorption site of the nitrogen atoms and the arsenic atoms.

10 Regarding the plane orientation of the substrate, in light of the above-described functions of this example, a group III plane and a group V plane can be alternately exposed. A {100} plane and a plane obtained by inclining the {100} plane at 2 to 15 degrees are preferable.

15

 In this example, the supply amounts of the source materials are controlled in terms of the supply amounts per unit time and the supply time. The supply amount of the source materials are unquestionably better controlled
20 by controlling the supply sequence while monitoring the vibration phase of the reflection high energy electron beam diffraction (RHEED). In addition, a wait time (a time period in which no material is supplied) may be provided after each source material is supplied in order

to expel the remaining material. It is especially preferable to provide a wait time after supply of a group V material, which is supplied in a relatively large amount per unit time.

5

In this example, an AlGaAs/AlGaInAs/AlGaAs structure was produced. The upper and lower barrier layers may be formed of AlGaAs, containing GaAs, having a different Al-mix crystal ratio, GaInP, InGaAsP, AlGaInP
10 or other materials.

(Example 16)

In this example, a semiconductor laser 100 shown in Figure 7 having an oscillation wavelength of 1.3 μm
15 was produced. The wavelength of 1.3 μm , at which the dispersion in wavelength of a quartz-based optical fiber is at a minimum, is important in optical communications using an optical fiber. The semiconductor laser 100 includes an n-type GaAs substrate (300 μm) 11, an n-type
20 GaAs buffer layer (0.5 μm) 12, an n-type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ lower cladding layer (1 μm) 13, a non-doped $\text{Al}_{0.05}\text{Ga}_{0.95}\text{As}$ guide layer (0.1 μm) 14a, a non-doped $\text{Al}_{0.05}\text{Ga}_{0.64}\text{In}_{0.31}\text{N}_{0.015}\text{As}_{0.985}$ well layer (compression strain: 2%; 6 nm) 15, a non-doped $\text{Al}_{0.05}\text{Ga}_{0.95}\text{As}$ guide layer (0.1 μm) 14b, a p-type $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$

upper cladding layer (1 μm) 16, a p-type GaAs contact layer (0.5 μm) 17, and a polyimide current constriction layer 18. The layers 12 through 17 are laminated on the GaAs substrate 11. The semiconductor laser 100 also
5 includes an AuGe electrode metal 19a and an AuZn electrode metal 19b interposing the laminate.

Hereinafter, a method for forming a compound semiconductor layer in this example will be described.
10 The method is different from the conventional methods in that an appropriate amount of Al source material is added during the crystal growth of a quantum well layer in this example.

15 An MBE apparatus containing a Ga source material, an In source material, an Al source material and an As source material as solid sources, and NH_3 (ammonia) as a gas source was used. The substrate 11 was irradiated with a molecular beam of each source material while maintaining
20 the temperature of the GaAs substrate 11 having a {100} plane as a principal plane at 600°C, thereby performing crystal growth. Thus, a multi-layer film including the buffer layer 12, the lower cladding layer 13, the guide layer 14a, the well layer 15, the guide layer 14b, the

upper cladding layer 16, and the contact layer 17 was produced. NH_3 as the gas source was supplied by performing cracking using alumina. As dopants for controlling conductivity types, solid Si was used for
5 doping with Si, and solid Be was used for doping with Be. The growth rate was set to be $0.5 \mu\text{m}/\text{time}$. All the necessary source materials were concurrently supplied for growing each layer. Especially in producing an AlGaInNAs layer as the well layer 15, Al and NH_3 were concurrently
10 supplied.

After the multi-layer film was crystal-grown by the MBE method, the contact layer 17 and a part of the upper cladding layer 16 were etched into a stripe having
15 a width of $3 \mu\text{m}$, thereby forming a ridge-type waveguide structure. On side surfaces of the ridge, the current constriction layer 18 of polyimide was formed. Then, the upper and lower electrodes 19a and 19b were formed. Thus, the semiconductor laser 100 was produced.

20

The semiconductor laser 100 produced in this manner oscillated at room temperature at an oscillation threshold current of 20 mA to emit light having a wavelength of $1.3 \mu\text{m}$. The characteristic temperature

was 180 K. As a result of performing an aging test at 80°C and 10 mW, the semiconductor laser device was confirmed to stably operate for 5000 hours or more.

5 When mix-crystallizing Al with a $\text{Ga}_{0.7}\text{In}_{0.3}\text{N}_{0.01}\text{As}_{0.99}$ well layer which emits light having a wavelength of 1.3 μm , expansion of the forbidden band caused by the mix-crystallization of Al can be cancelled so as to maintain the oscillation wavelength (at 1.3 μm) by increasing the
10 nitrogen and indium-mix crystal ratios. Figure 8 shows the relationship between the Al-mix crystal ratio x and the conditions of the nitrogen and indium-mix crystal ratios required to maintain the wavelength at 1.3 μm . It can be appreciated from Figure 8 that when, for example,
15 the Al-mix crystal ratio x is 0.05 as in this example, the nitrogen-mix crystal ratio needs to be increased to about 1.36 times higher than the case in which Al is not mix-crystallized.

20 In this example, $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ was used for the cladding layers, and $\text{Al}_{0.05}\text{Ga}_{0.95}\text{As}$ was used for the guide layers. The cladding layers, the guide layers and the barrier layers may be formed of a material which can be represented as $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0$, $i > 0$, $j \geq 0$), for

example, AlGaAs, containing GaAs, having a different Al-mix crystal ratio, GaInP, InGaAsP, AlGaInP or other materials, since these materials have an optimum growth temperature in the optimum growth temperature range for AlGaInNAs used for the well layer.

(Comparative example 15)

A semiconductor laser for emitting light having a wavelength of 1.3 μm was produced in a similar manner to that of Example 16 except that the well layer 15 in Figure 7 was formed of $\text{Ga}_{0.7}\text{In}_{0.3}\text{N}_{0.01}\text{As}_{0.99}$, which does not contain Al and that crystal growth was performed at a growth temperature of 500°C in order to introduce nitrogen. In this case, the oscillation threshold was 65 mA and the characteristic temperature was 105 K, which were inferior to those of the semiconductor laser device in Example 16. The reason is that when Al is not contained in the well layer, crystal growth needs to be performed at a temperature which is relatively low as the growth temperature of a group III-V compound, in order to introduce nitrogen. It is considered that the crystal of the well layer did not have satisfactory crystallinity and thus sufficient optical gain was not obtained due to such a low growth temperature.

Figure 9 is a graph illustrating the oscillation threshold current of the semiconductor laser in Example 16 having an Al-mix crystal ratio of 0.05 in the well layer, and semiconductor lasers having a structure similar to that of the semiconductor laser in Example 16 except having an Al-mix crystal ratio of 0, 0.02, 0.1, 0.15, 0.2 and 0.25 in the well layer. For each semiconductor laser, the nitrogen-mix crystal ratio and the indium-mix crystal ratio were adjusted in accordance with the relationship shown in Figure 8 in order to maintain the oscillation wavelength at 1.3 μm . For the device having an Al-mix crystal ratio of zero, crystal growth was performed at a growth temperature of 500°C in order to introduce nitrogen.

In general, when nitrogen is mix-crystallized with an arsenic compound, the crystallinity is drastically deteriorated as the nitrogen-mix crystal ratio increases. However, the devices produced by the method of the present invention with an Al-mix crystal ratio in the range of 0.02 to 0.20 exhibited an oscillation threshold current lower than that of a device produced with an Al-mix crystal ratio of zero, despite the

increased nitrogen-mix crystal ratio as the Al-mix crystal ratio increased. The devices produced with an Al-mix crystal ratio in the range of 0.02 to 0.10 were especially superior with an oscillation threshold current
5 being half or less of that of a device produced by the conventional methods. A device produced with an Al-mix crystal ratio x of 0.25 exhibited an oscillation threshold current which was higher than that of a device produced by the conventional methods. As can be appreciated from
10 Figure 8, the nitrogen-mix crystal ratio in the well layer of the device produced with an Al-mix crystal ratio x of 0.25 was about three times higher than that of the device produced with an Al-mix crystal ratio of zero. Such a deterioration in the crystallinity caused by an increase
15 in the nitrogen-mix crystal ratio resulted in a decline in the device characteristics.

In Example 16, the semiconductor laser for emitting light at a wavelength of 1.3 μm was produced.
20 The oscillation wavelength is not limited to 1.3 μm , but can be arbitrarily selected to be, for example, 1.2 μm or 1.55 μm in accordance with the intended application. In this example, a surface emission semiconductor laser having a Fabry-Perot resonator is described. A

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distributed feedback semiconductor laser, a distributed reflection semiconductor laser, a vertical resonator surface emission laser, or a light-emitting diode, for example, can be similarly structured. As the active
5 layer, a strained quantum well active layer having a compression strain was described. The direction and amount of strain can be arbitrarily selected. The active layer may be a bulk active layer, a quantum fine line active layer, or a quantum box active layer.

10

(Example 17)

A multi-layer film having a structure shown in Figure 1 was produced in a similar manner to that of Example 1 except that the upper barrier and the lower barrier layer
15 were formed of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ which is lattice-matched to the GaAs substrate and that the substrate temperature was set to be 600°C. The substrate temperature was kept constant while crystal growth was performed to form the multi-layer film.

20

(Example 18)

A multi-layer film having a structure shown in Figure 1 was produced in a similar manner to that of Example 1 except that the upper barrier and the lower barrier layer

were formed of $(\text{Al}_{0.3}\text{Ga}_{0.7})_{0.5}\text{In}_{0.5}\text{P}$ which is lattice-matched to the GaAs substrate and that the substrate temperature was set to be 600°C. The substrate temperature was kept constant while crystal growth was performed to form the multi-layer film.

(Example 19)

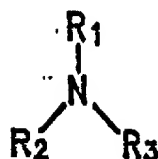
A multi-layer film having a structure shown in Figure 1 was produced in a similar manner to that of Example 1 except that the upper barrier and the lower barrier layer were formed of $\text{In}_{0.43}\text{Ga}_{0.57}\text{As}_{0.2}\text{P}_{0.8}$ which is lattice-matched to the GaAs substrate and that the substrate temperature was set to be 600°C. The substrate temperature was kept constant while crystal growth was performed to form the multi-layer film.

In the single quantum well in Examples 17 through 19, the photoluminescence light emission intensity from the $\text{Al}_{0.03}\text{Ga}_{0.95}\text{N}_{0.015}\text{As}_{0.005}$ well layer was substantially equal to that in Examples 1 through 16 in which the barrier layers were formed of AlGaAs.

In all of the above examples, an appropriate material is usable as the Ga source material, In source

material, Al source material and As source material. For example, usable Ga source materials include organic metal compounds such as, for example, metal Ga, TMGa and TEGa (triethyl gallium) and chlorides such as, for example, GaCl₃. Usable In source materials include, for example, organic metal compounds such as, for example, metal In and TMin. Usable Al source materials include, for example, organic metal compounds such as, for example, metal Al and TMAI. Usable As source materials include, for example, organic metal compounds such as, for example, As₄ and As₂, obtained from metal As and TMAs (trimethyl arsine), and hydrides such as, for example, AsH₃.

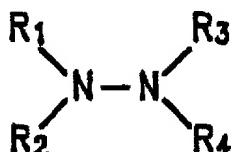
In the above examples, ammonia is used as a nitrogen source material. The effect of the decomposition of the source material being promoted at the surface of an active crystal containing Al can be similarly provided by other nitrogen source materials including ammonia and organic compounds thereof represented by:



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or hydrazine and organic compounds thereof represented by:

10



- 15 In the above formulas, R_1 , R_2 , R_3 and R_4 are each hydrogen or a lower alkyl group. Alternatively, a nitrogen compound containing nitrogen atoms which are radical-excited is usable as the nitrogen source material. According to the present invention, these materials can
- 20 be crystal-grown at a higher temperature than in the conventional methods, and thus nitrogen atoms can be introduced with high efficiency. The source materials to be supplied may contain indium (In) as a group III element and phosphorus (P) as a group V element.

Specifically, since In has a high pressure when vaporized and is easily thermally evaporated, concurrent addition of Al and In is convenient since it provides another effect of suppressing thermal evaporation of In.

5

In the above examples, compound semiconductors appropriately containing Ga, In and Al as group III elements and As and N as group V elements are shown. Other group III elements (for example, B), other group V
10 elements (for example, Sb and P), and impurity elements (for example, Zn, Be, Mg, Te, S, Se and Si) can be appropriately contained.

In all of the above examples, GaAs is used as the
15 material for the substrate. The material for the substrate is not limited to GaAs. Other materials can be used to provide similar effects. For example, other group III-V compound semiconductor substrates such as an InGaAs substrate, group II-VI compound semiconductor
20 substrates such as a ZnS substrate, and group IV compound semiconductor substrates such as a Ge substrate are usable.

In the above examples, the MBE method and the CBE

method are used as the method for crystal growth. An
MO-MBE (metal organic molecular beam epitaxy) method, a
GS-MBE (gas source molecular beam epitaxy) method, an
MOCVD method, a hydride VPE method, and a chloride VPE
5 method can be used to provide similar effects.

Throughout this specification, the term "upper"
refers to a position farther from the substrate, and the
term "lower" refers to a position closer to the substrate.
10 Crystal growth proceeds in the direction from "lower" to
"upper".

The present invention is not limited to the
above-described combinations of crystal composition,
15 band gap wavelength, and hetero junction. Needless to
say, the present invention is applicable to production
of a group III-V compound semiconductor mixed-crystal
having other compositions and bandgaps, which contains
both nitrogen (N) and arsenic (As) as group V elements.
20 The present invention is not limited to a structure in
which the grown layers are lattice-matched to the crystal
of the substrate. The grown layers may contain a material
which is lattice-mismatched to the crystal of the
substrate so long as crystal defects are not induced. For

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example, a strained quantum well structure of a semiconductor laser can be used.

INDUSTRIAL APPLICABILITY

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10 The present invention provides a method for forming a compound semiconductor formed of group III-V semiconductor materials containing group III-V compound semiconductors which contain arsenic as a group V element, and also containing nitrogen mix-crystallized therewith, and specifically a method for forming a crystal having satisfactory light emission characteristics. More specifically, even when the growth temperature is increased to be substantially as high as the optimum crystal growth temperature for AlGaAs or the like, a sufficient amount of nitrogen can be mix-crystallized. Accordingly, a method for forming a compound semiconductor layer which is convenient to a structure for light emitting devices, including semiconductor lasers can be provided. In addition, a compound semiconductor device having superb characteristics can be provided by applying the formation method of the present invention. Especially, a compound semiconductor film having crystallinity and light emission

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characteristics which are sufficient for a light emission layer of a light emitting device can be produced. Thus, a device having superb light emission characteristics, light emission efficiency, and device life can be
5 provided.

1998-03-24

CLAIMS

1. (Amended) A method for forming a compound semiconductor layer, comprising the step of crystal-
5 growing a group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements on a single crystal substrate,

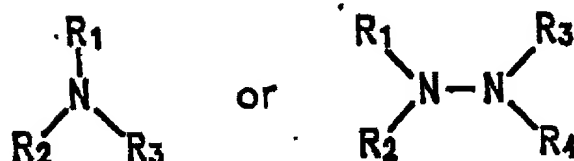
wherein the step of crystal-growing the compound semiconductor layer includes the step of supplying an
10 aluminum source material to the single crystal substrate concurrently with a nitrogen source material.

15 2. A method for forming a compound semiconductor layer according to claim 1, wherein an aluminum-mix crystal ratio in a group III element in the compound semiconductor layer is 0.02 or higher.

20 3. A method for forming a compound semiconductor layer according to claim 1, wherein the step of crystal-growing the compound semiconductor layer is performed at a temperature of the single crystal substrate in the range of 500°C or higher and 750°C or lower.

4. A method for forming a compound semiconductor layer according to claim 1, wherein the nitrogen source material contains

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where R_1 , R_2 , R_3 and R_4 are hydrogen or a lower alkyl group.

5. A method for forming a compound semiconductor layer according to claim 1, wherein more than 0% and less than 50% of the crystal growth surface of the compound semiconductor layer is covered with group V atoms.

15

6. A method for forming a compound semiconductor layer according to claim 1, further comprising the step of crystal-growing a layer formed of $Al_hGa_iIn_{1-h-i}As_jP_{1-j}$ ($h \geq 0$, $i > 0$, $j \geq 0$) on the single crystal substrate, wherein the step of crystal-growing the compound semiconductor layer and the step of growing the crystal formed of $Al_hGa_iIn_{1-h-i}As_jP_{1-j}$ are performed at the same temperature.

20

7. A method for forming a compound semiconductor layer according to claim 6, wherein the step of crystal-growing the compound semiconductor layer is performed after the step of crystal-growing the layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$.

8. A method for forming a compound semiconductor layer according to claim 6, wherein the step of crystal-growing the compound semiconductor layer is performed before the step of crystal-growing the layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$.

9. A method for forming a compound semiconductor layer according to claim 1, wherein the compound semiconductor layer further contains indium.

10. (Amended) A method for forming a compound semiconductor layer, comprising the step of crystal-growing a group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements on a single crystal substrate, wherein the step of crystal-growing the compound semiconductor layer includes the step of supplying a nitrogen source material to the single crystal substrate so that the nitrogen source material interacts with aluminum at least on a crystal growth surface of the compound semiconductor layer.

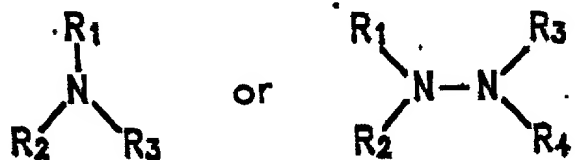
aluminum source material to the single crystal substrate concurrently with a nitrogen source material.

11. A method for forming a compound semiconductor layer according to claim 10, wherein an aluminum-mix crystal ratio in a group III element in the compound semiconductor layer is 0.02 or higher.

12. A method for forming a compound semiconductor layer according to claim 10, wherein the step of crystal-growing the compound semiconductor layer is performed at a temperature of the single crystal substrate in the range of 500°C or higher and 750°C or lower.

13. A method for forming a compound semiconductor layer according to claim 10, wherein the nitrogen source material contains

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where R_1 , R_2 , R_3 and R_4 are hydrogen or a lower alkyl group.

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14. A method for forming a compound semiconductor layer according to claim 10, wherein more than 0% and less than 50% of the crystal growth surface of the compound semiconductor layer is covered with group V atoms.

15. A method for forming a compound semiconductor layer according to claim 10, further comprising the step of crystal-growing a layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0, i > 0, j \geq 0$) on the single crystal substrate, wherein the step of crystal-growing the compound semiconductor layer and the step of growing the crystal formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ are performed at the same temperature.

16. A method for forming a compound semiconductor layer according to claim 15, wherein the step of crystal-growing the compound semiconductor layer is performed after the step of crystal-growing the layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$.

20

17. A method for forming a compound semiconductor layer according to claim 15, wherein the step of crystal-growing the compound semiconductor layer is performed before the step of crystal-growing the layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$.

$\text{As}_x\text{P}_{1-x}$.

18. A method for forming a compound semiconductor layer according to claim 10, wherein the compound semiconductor layer further contains indium.

19. A method for forming a compound semiconductor layer, comprising the step of crystal-growing a group III-V compound semiconductor layer containing at least nitrogen and arsenic as group V elements on a single crystal substrate,

wherein the step of crystal-growing the compound semiconductor layer includes the step of supplying a nitrogen source material to a crystal surface of the compound semiconductor layer in a state where the group III atoms containing aluminum are exposed to the crystal surface.

20. A method for forming a compound semiconductor layer according to claim 19, wherein an aluminum-mix crystal ratio in a group III element in the compound semiconductor layer is 0.02 or higher.

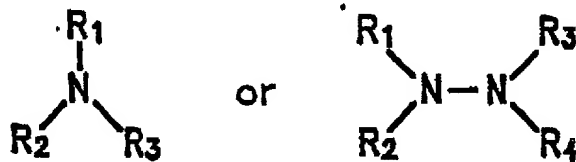
21. A method for forming a compound semiconductor layer

according to claim 19, wherein the step of crystal-growing the compound semiconductor layer is performed at a temperature of the single crystal substrate in the range of 500°C or higher and 750°C or lower.

5

22. A method for forming a compound semiconductor layer according to claim 19, wherein the nitrogen source material contains

10



15 where R₁, R₂, R₃, and R₄ are hydrogen or a lower alkyl group.

23. A method for forming a compound semiconductor layer according to claim 19, wherein more than 0% and less than 50% of the crystal growth surface of the compound
20 semiconductor layer is covered with group V atoms.

24. A method for forming a compound semiconductor layer according to claim 19, wherein the step of crystal-growing the compound semiconductor layer further includes the

step of supplying a group III source material containing aluminum and the step of supplying an arsenic source material, wherein a process sequentially including the step of supplying the group III source material, the step of supplying the nitrogen source material, and the step of supplying the arsenic source material is performed at least once.

25. A method for forming a compound semiconductor layer according to claim 24, wherein the single crystal substrate has a {100} plane as a principal plane.

26. A method for forming a compound semiconductor layer according to claim 19, further comprising the step of crystal-growing a layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0, i > 0, j \geq 0$) on the single crystal substrate, wherein the step of crystal-growing the compound semiconductor layer and the step of growing the crystal formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ are performed at the same temperature.

27. A method for forming a compound semiconductor layer according to claim 26, wherein the step of crystal-growing the compound semiconductor layer is performed after the step of crystal-growing the layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h}$.

$\text{As}_j\text{P}_{1-j}$.

28. A method for forming a compound semiconductor layer according to claim 26, wherein the step of crystal-growing
5 the compound semiconductor layer is performed before the step of crystal-growing the layer formed of $\text{Al}_n\text{Ga}_1\text{In}_{1-n}$ - $\text{As}_j\text{P}_{1-j}$.

29. A method for forming a compound semiconductor layer
10 according to claim 19, wherein the compound semiconductor layer further contains indium.

30. (Amended) A compound semiconductor apparatus,
comprising at least one group III-V compound
15 semiconductor layer containing at least aluminum as a group III element and containing at least nitrogen and arsenic as group V elements.

31. (Amended) A compound semiconductor apparatus according to claim 30, wherein the compound semiconductor apparatus is a light emitting device including at least a light emitting layer, and the light emitting layer includes the compound semiconductor layer.

32. (Added) A compound semiconductor apparatus according to claim 31, wherein the light emitting layer is formed of $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{N}_z\text{As}_{1-z}$ ($0 < x, y, z < 1$), wherein an Al-mix crystal ratio x in the light emitting layer is 0.02 or higher and 0.20 or lower.

33. (Added) A compound semiconductor apparatus according to claim 31 or 32, wherein the light emitting device further includes a cladding layer, a guide layer and/or a barrier layer formed of $\text{Al}_h\text{Ga}_i\text{In}_{1-h-i}\text{As}_j\text{P}_{1-j}$ ($h \geq 0, i > 0, j \geq 0$).

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ABSTRACT

Includes the step of crystal-growing a group III-V compound semiconductor layer containing at least nitrogen
5 and arsenic as group V elements on a single crystal substrate. The step of crystal-growing the compound semiconductor layer includes the step of supplying a nitrogen source material to the single crystal substrate so that the nitrogen source material interacts with
10 aluminum at least on a crystal growth surface of the compound semiconductor layer. Thus, a method is provided for forming a group III-V compound semiconductor layer containing a group III-V compound semiconductor containing arsenic as a group V element and also
15 containing nitrogen mix-crystallized therewith, which has superb light emission characteristics.

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FIG. 1

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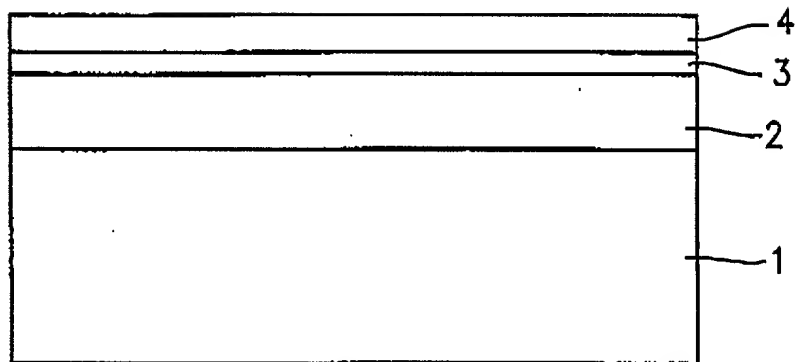


FIG. 2

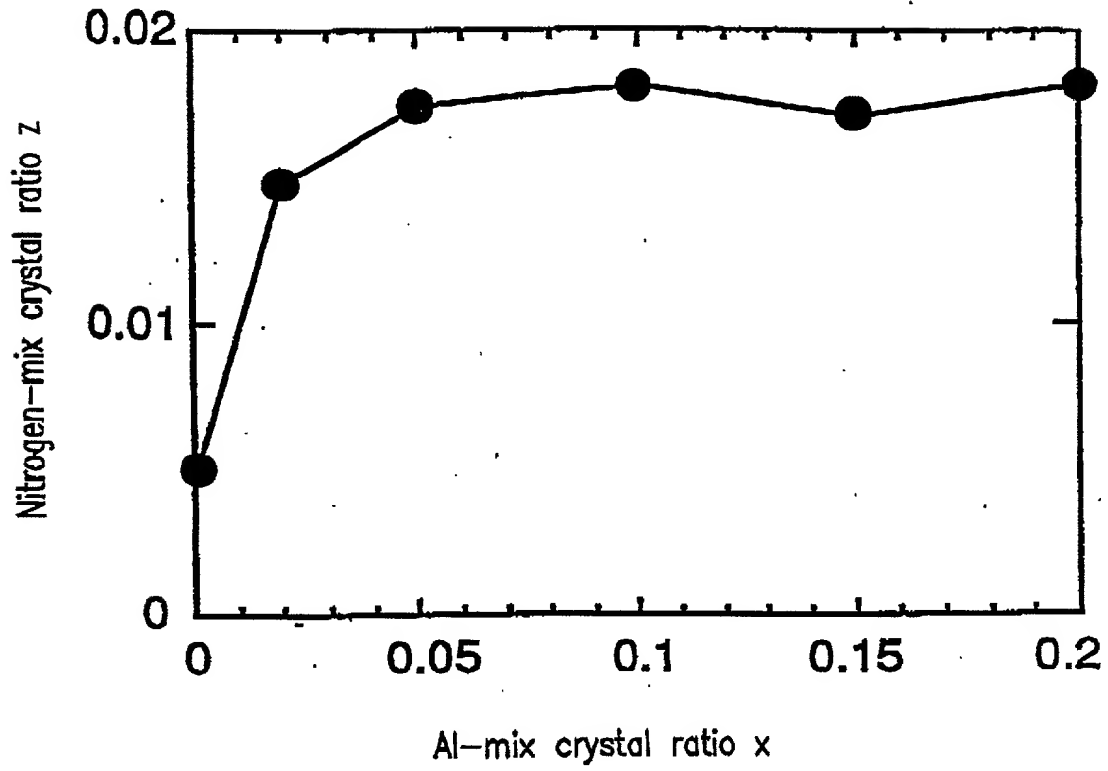


FIG. 3

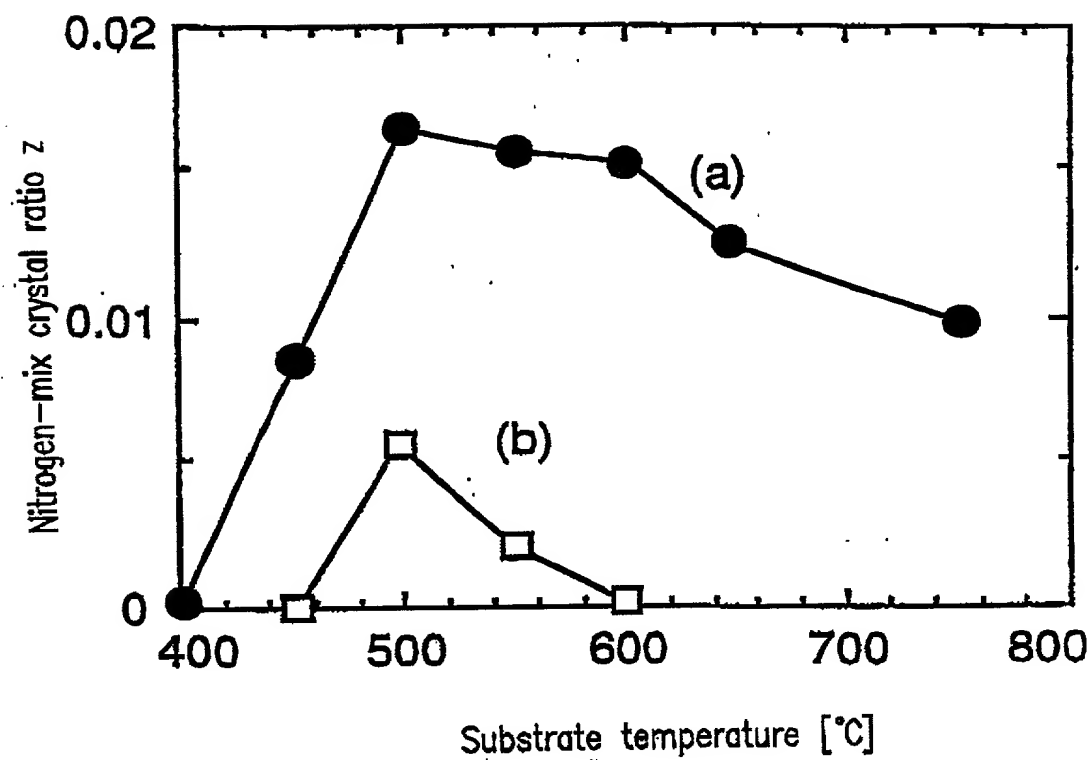
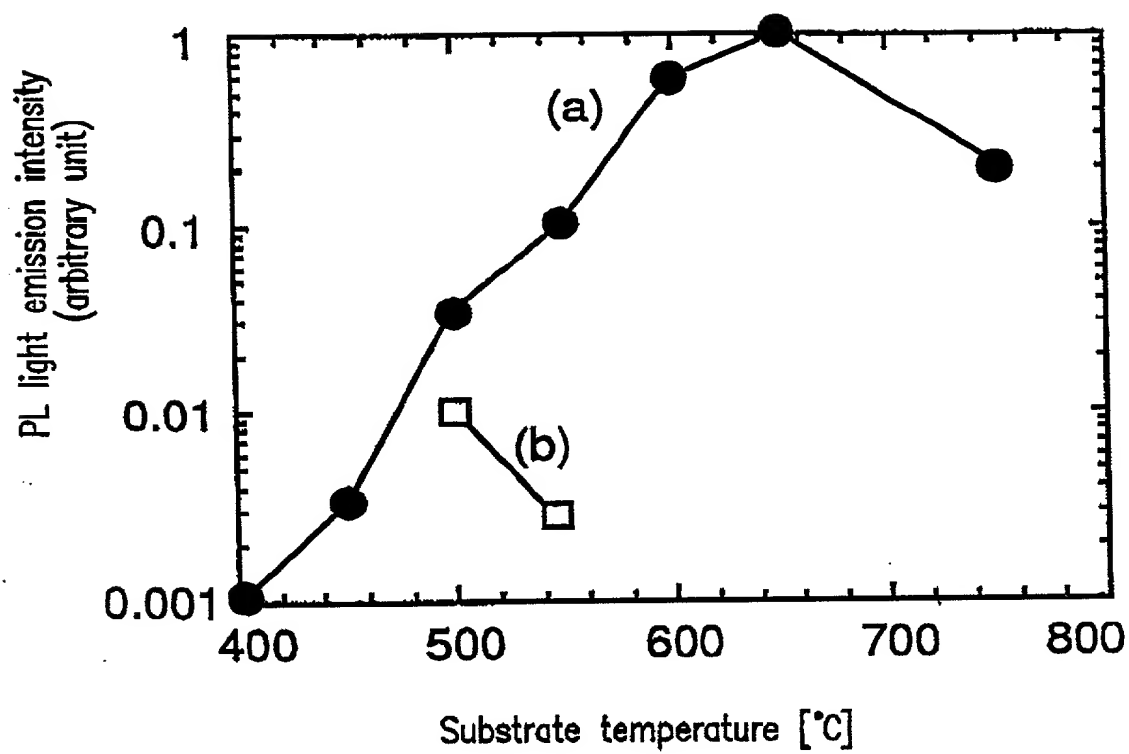


FIG. 4



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FIG. 5

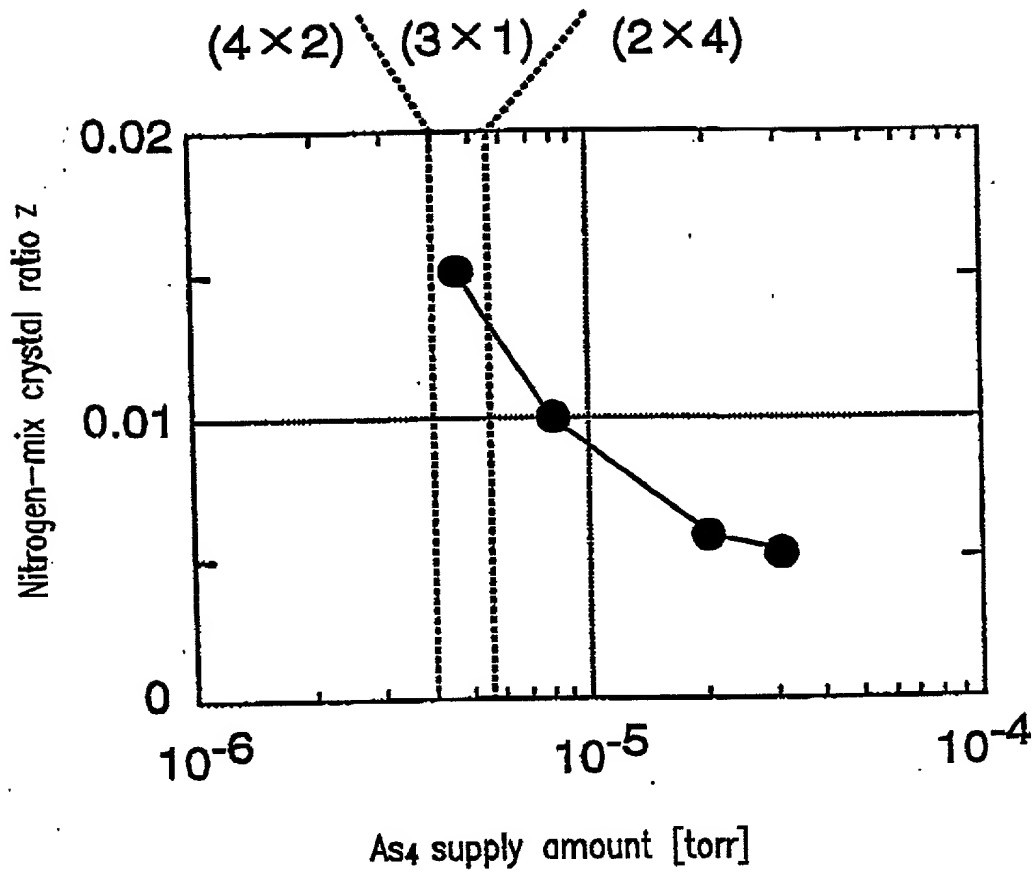
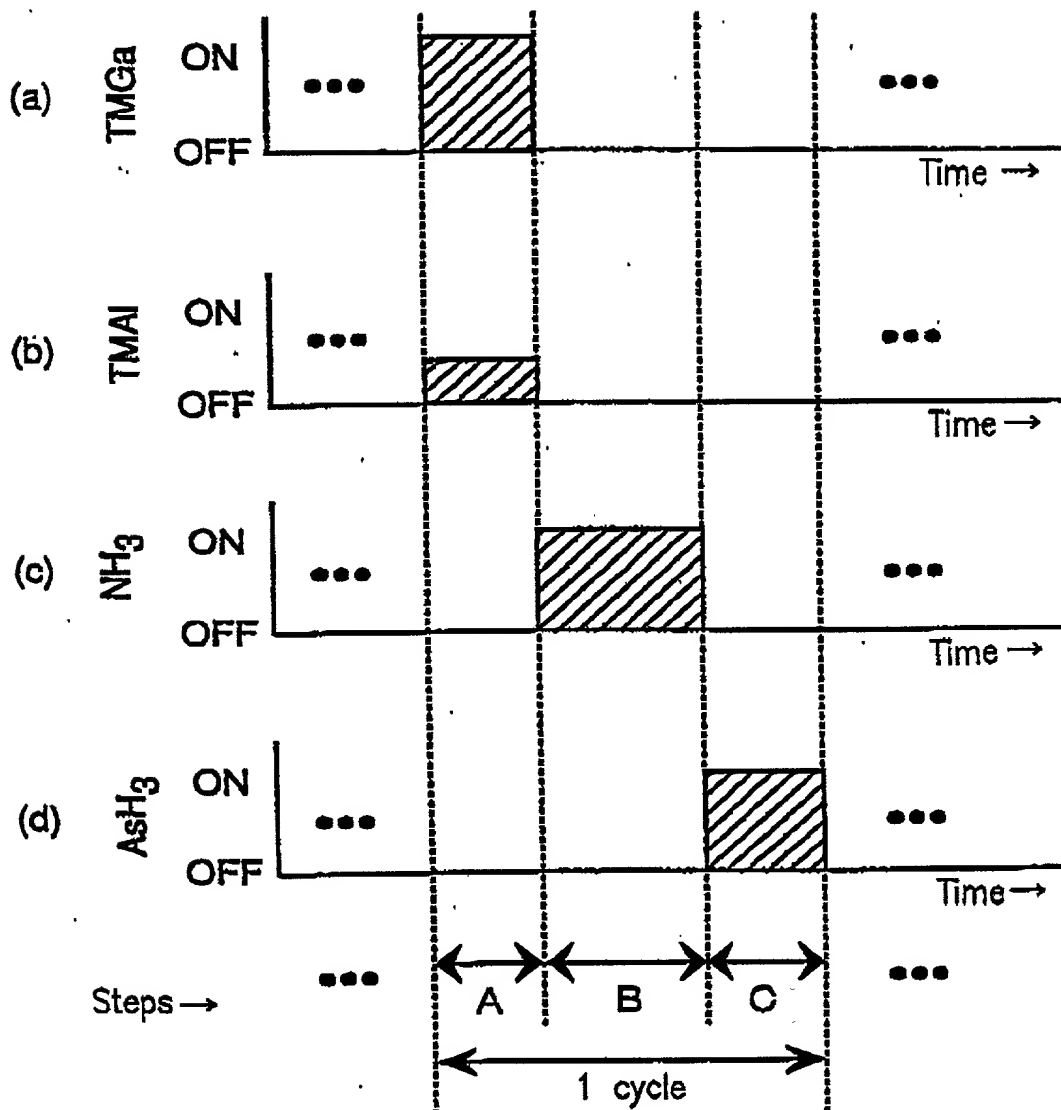


FIG. 6



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FIG. 7

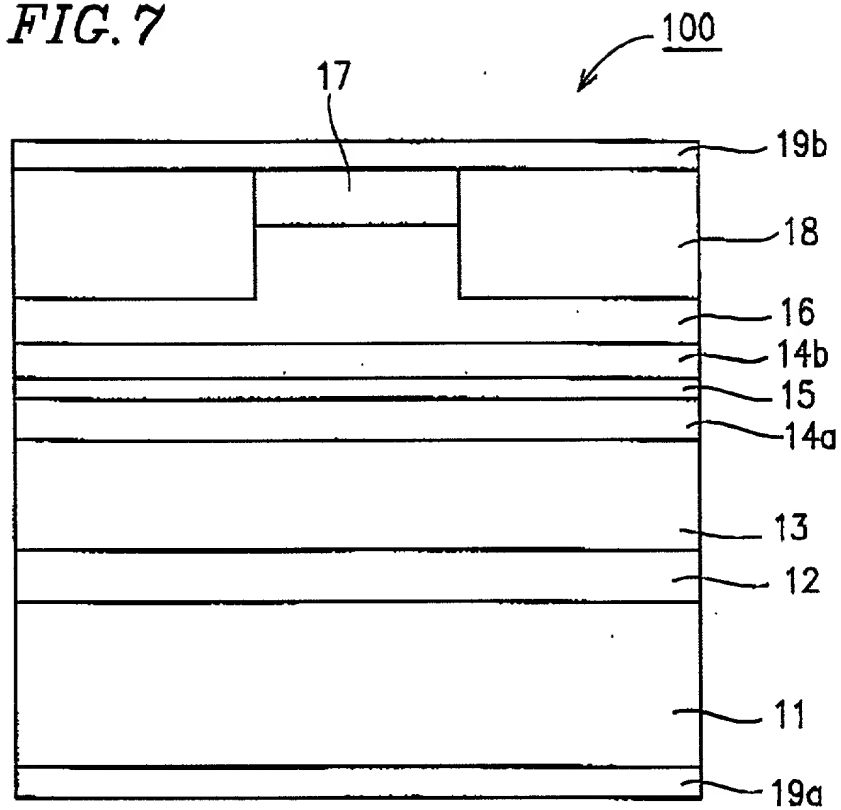


FIG. 8

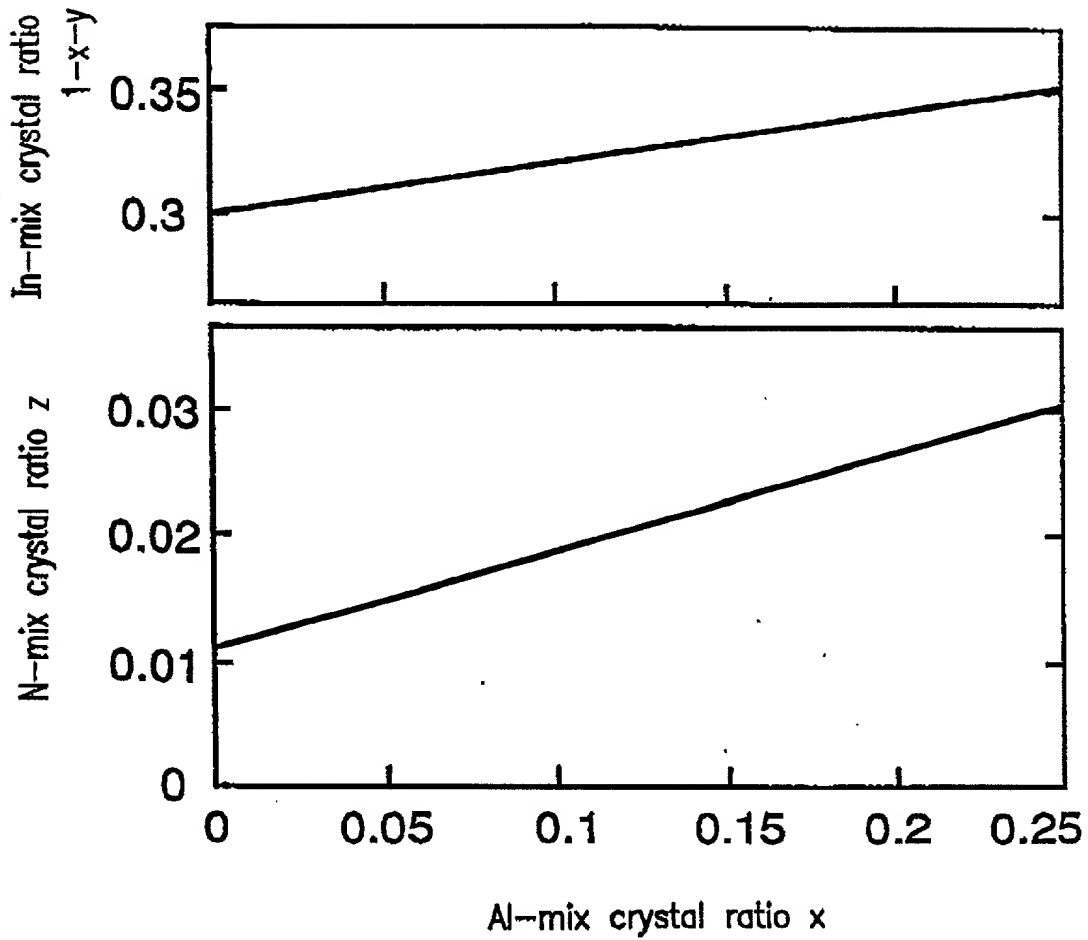
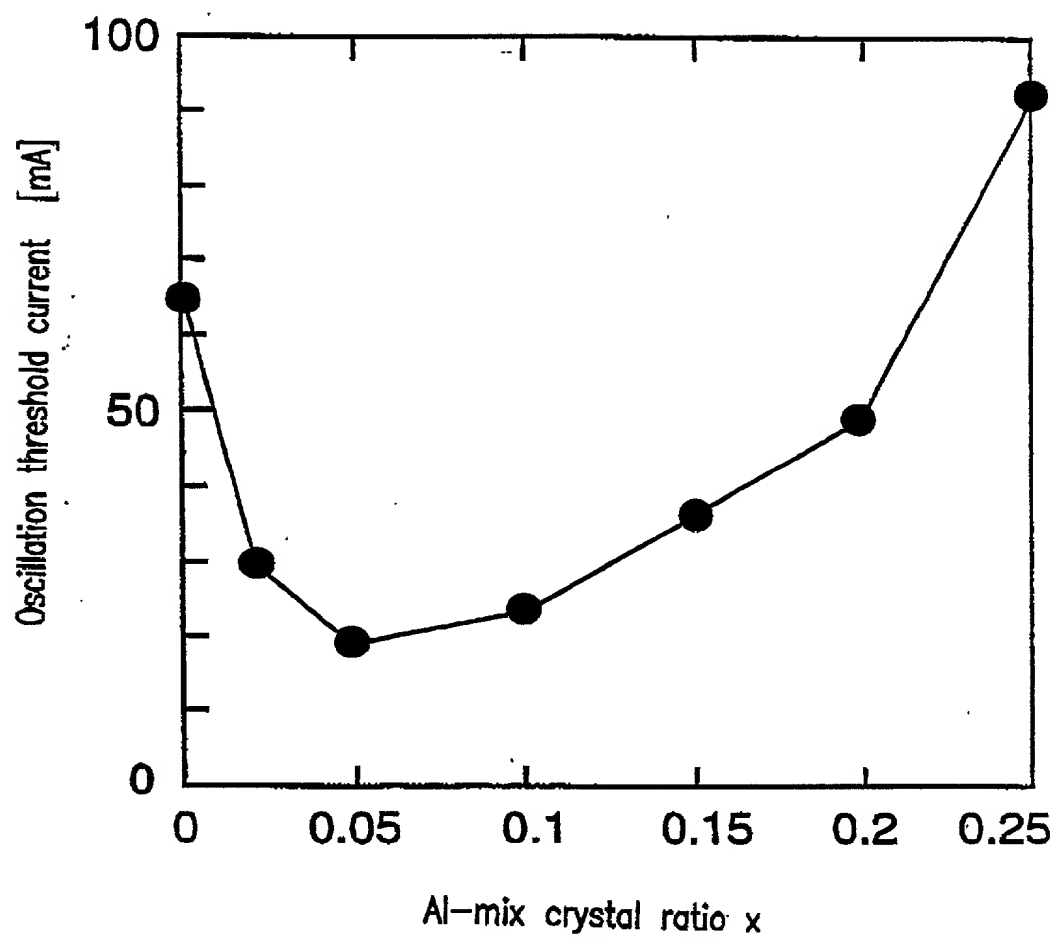


FIG. 9



#3

Declaration and Power of Attorney For Patent Application

特許出願宣言書及び委任状

Japanese Language Declaration

日本語宣言書

下記の氏名の発明者として、私は以下の通り宣言します。

As a below named inventor, I hereby declare that:

私の住所、私書箱、国籍は下記の私の氏名の後に記載された通りです。

My residence, post office address and citizenship are as stated next to my name.

下記の名称の発明に関して請求範囲に記載され、特許出願している発明内容について、私が最初かつ唯一の発明者（下記の氏名が一つの場合）もしくは最初かつ共同発明者であると（下記の名称が複数の場合）信じています。

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

METHOD FOR FORMING COMPOUND SEMICONDUCTOR

LAYER AND COMPOUND SEMICONDUCTOR APPARATUS,

上記発明の明細書（下記の欄でx印がついていない場合は、本書に添付）は、

the specification of which is attached hereto unless the following box is checked:

☐ 月 日に提出され、米国出願番号または特許協定条約国際出願番号を _____ とし、
(該当する場合) _____ に訂正されました。

☒ was filed on March 12, 2001
as United States Application Number or
PCT International Application Number
09/786,977 and was amended on
_____ (if applicable).

私は、特許請求範囲を含む上記訂正後の明細書を検討し、内容を理解していることをここに表明します。

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

私は、連邦規則法典第37編第1条56項に定義されるとおり、特許資格の有無について重要な情報を開示する義務があることを認めます。

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

Japanese Language Declaration

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私は、米国法典第35編119条(a)-(d)項又は365条(b)項に基づき下記の、米国外の国の少なくとも一カ国を指定している特許協力条約365(a)項に基づく国際出願、又は外国での特許出願もしくは発明者証の出願についての外国優先権をここに主張するとともに、優先権を主張している。本出願の前に出願された特許または発明者証の外国出願を以下に、枠内をマークすることで、示しています。

Prior Foreign Application(s)

外国での先行出願

10-259015

Japan

(Number)

(番号)

(Country)

(国名)

(Number)

(番号)

(Country)

(国名)

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(Application No.)

(出願番号)

(Filing Date)

(出願日)

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(Application No.)

(出願番号)

(Filing Date)

(出願日)

(Application No.)

(出願番号)

(Filing Date)

(出願日)

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I hereby claim foreign priority under Title 35, United States Code, Section 119 (a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or PCT International application having a filing date before that of the application on which priority is claimed.

Priority Not Claimed

優先権主張なし

11, September 1998

(Day/Month/Year Filed)

(出願年月日)

(Day/Month/Year Filed)

(出願年月日)

I hereby claim the benefit under Title 35, United States Code, Section 119(e) of any United States provisional application(s) listed below.

(Application No.)

(出願番号)

(Filing Date)

(出願日)

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s), or 365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of Title 35, United States Code Section 112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of application.

(Status: Patented, Pending, Abandoned)

(現況: 特許許可済、係属中、放棄済)

(Status: Patented, Pending, Abandoned)

(現況: 特許許可済、係属中、放棄済)

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Japanese Language Declaration (日本語宣言書)

委任状: 私は下記の発明者として、本出願に関する一切の
手続きを米特許商標局に対して遂行する弁理士または代理人
として、下記の者を指名いたします。(弁理士、または代理
人の氏名及び登録番号を明記のこと)

POWER OF ATTORNEY: As a named inventor, I hereby appoint
the following attorney(s) and/or agent(s) to prosecute this
application and transact all business in the Patent and Trademark
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